Balanced Polar Mercury Contact Relay

By J. T. L. BROWN and C. E. POLLARD

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A new type of relay moking use of solid contacts maintained continuously wet with mercury has been developed. It has a symmetricol polar structure, resulting in improved sensitivity ond spced compared with the existing neutrol structure with similar contacts. It is also porticulorly well odapted to switching of high frequency circuits. Two magnets are used for polorizotion, and the relay is adjusted after assembly to desired values of sensitivity for operotion in both forward and reverse directions by selective odjustment of the mognet strengths.

INTRODUCTION

In a previous paper[1] a mercury contact relay is described in which the contact elements are maintained wet with mercury through a capillary path to mercury reservoir below the contacts. The present paper describes a new design making use of this same mercury contact principle, but with a symmetrical polar structure which gives improvement in sensitivity and speed capabilities over the previous neutral structure.

VERTICAL RELAY

Fig. 1 shows one design of the relay, adapted for general use in a vertical position. It provides a single pole double throw magnetic switch in a sealed glass tube, enclosed along with an operating coil and polarizing magnets in a steel can with a medium octal plug base similar to the previous type relay (275 type).

Fig. 2 shows the glass enclosed magnetic switch element. The armature is a tapered reed welded to a tubular stem which is sealed in the glass at the lower end. Mercury, and gas under pressure are introduced through this tube, which is then welded closed. The magnetic working gaps are formed between the armature and fixed pole-pieces which are sealed in

[1] J. T. L. Brown and C. E. Pollard, Mercury Contact Relays, Elec. Eng., **66**, Nov., 1947.

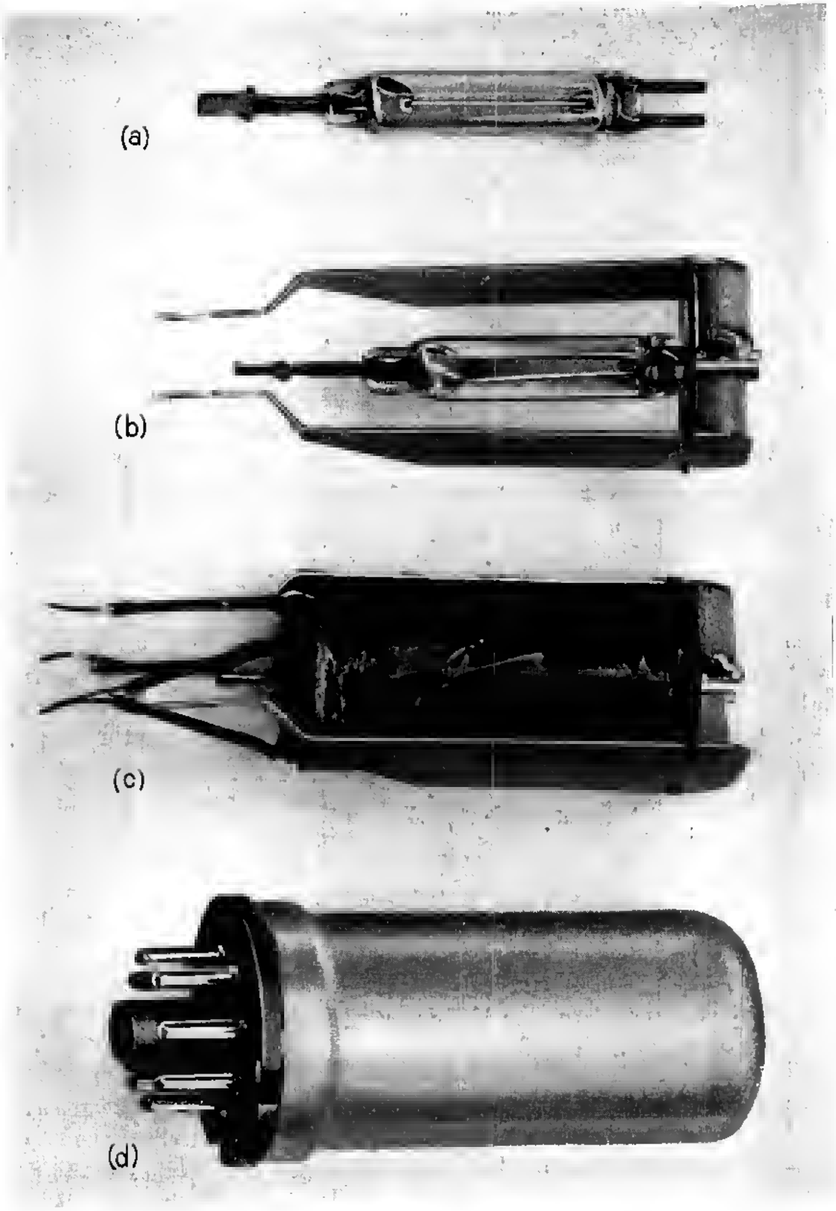

Fig. 1 — (a) Switch element. (b) Magnets, spool, and side plates added. (c) Coil added. (d) The complete relay.

the glass at the upper end. The fixed contacts are made from small platinum alloy balls which are welded to the pole-pieces. The armature strikes the fixed contacts at a point which is close to a node for one of its principal modes of vibration. This limits the bounce on impact to an amplitude which does not open the mercury bridge which is formed.

Mercury in a pool at the bottom of the switch is fed to the contact area through grooves rolled in the armature surface. Except for the platinum alloy contacts, the surfaces of the pole-pieces inside the switch have an oxide coating which prevents them from being wet by the mercury. This limits the mercury bridge which is formed between the armature and pole-piece to the area of the platinum alloy contact. A ceramic detail is inserted between the pole-pieces at the top of the switch. The ceramic is specially resistant to wetting by the mercury and thus prevents mercury from collecting between the pole-pieces.

The polarizing magnets are soldered to the pole-piece terminals outside the switch. Permalloy plates are soldered to the outer poles of the magnets and extend down on the outside of the coil, forming a return path to the lower end of the armature. The coupling at the lower end is made relatively loose in order to limit magnetic soak effects. The steel can provides a magnetic shield.

STATIC MERCURY CONFIGURATION

The static configuration of the mercury surfaces in the switch depends upon the shape and contact angle to mercury of the solid surfaces with which it comes in contact, and the curvature of the free mercury surfaces. This curvature depends on the surface tension of the mercury surface T and the pressure difference Δp between the inside and outside of the mercury at the point under consideration. That is,

$$\Delta p = T\left(\frac{1}{R_1} + \frac{1}{R_2}\right), \tag{1}$$

where R_1 and R_2 are principal radii of curvature of the surface (radii taken in planes cutting the surface at right angles to each other).

In this switch the pressure difference is a function of the height of the point under consideration above the surface of the reservoir:

$$\Delta p = \rho g h. \tag{2}$$

Substituting the values

$$\begin{aligned} \rho &= 13.6 \text{ g/cc for mercury,} \\ g &= 980 \text{ cm/sec}^2\text{, and} \\ T &= 450 \text{ dynes/cm for mercury,} \end{aligned}$$

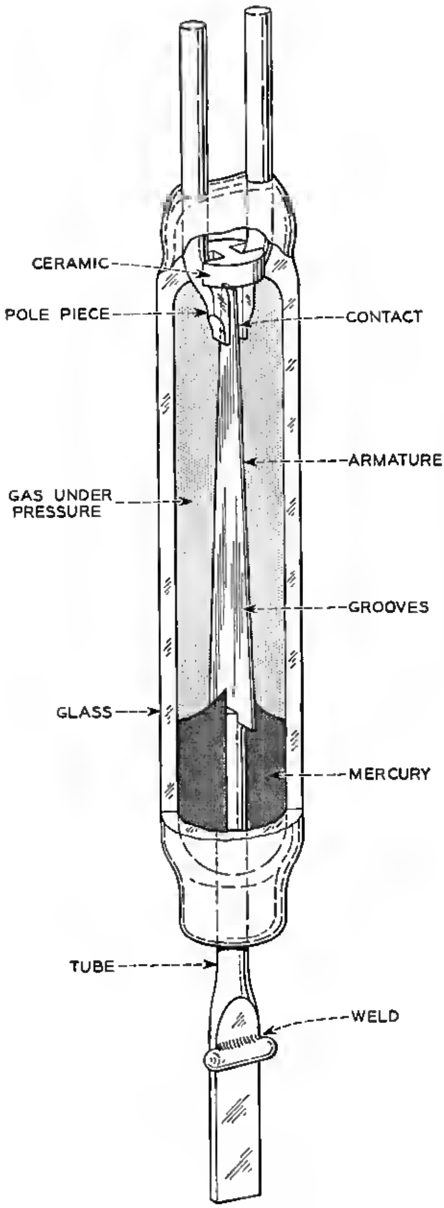

Fig. 2 — Vertical switch.

we obtain

$$h = 0.0338 \left(\frac{1}{R_1} + \frac{1}{R_2}\right) \text{ cm.} \tag{3}$$

Fig. 3 shows a cross section of the armature and pole-piece at the contact, indicating the configuration of the mercury in tbe grooves and around a closed contact, as determined from equation (3). In tbe grooves, it will be noted, the surface is concave cylindrical, witb a radius of −0.0163 cm, providing a path from tbe reservoir at this height with nearly the full capacity of the groove. The contact angles to the armature

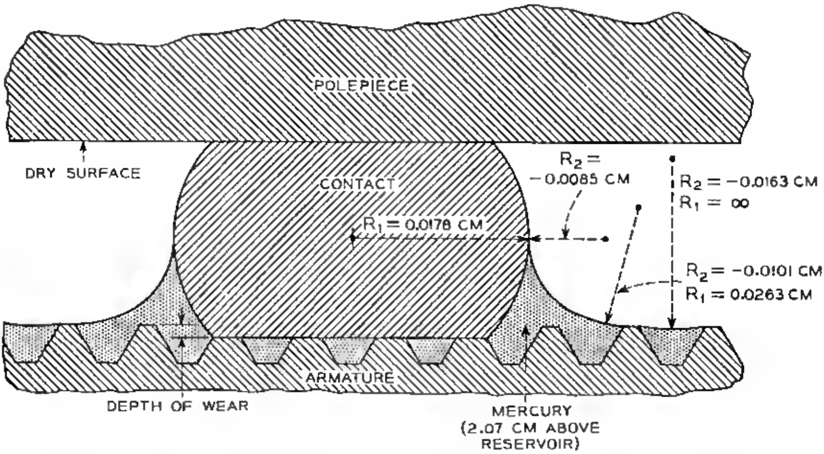

Fig. 3 — Cross-section showing configuration of mercury surface in grooves and around closed contact.

and platinum alloy contact surfaces are all zero, as these show complete wetting. The mercury fillet around the contact has positive curvature in the plane of the armature ($R_1 = +0.0178$ cm) and negative curvature ($R_2 = -0.0085$ cm) in planes through the axis of the contact.

The depth of wear indicated in Fig. 3 is brought to a stable value by an aging process in production.

DYNAMIC MERCURY CONFIGURATION

Fig. 4 shows flash photographs of the contacts at various instants during operation at 60 cps. It will be noted that, as the armature moves away from the fixed contact on the right, Figs. 4(a), (b) and (c), a bridge is drawn out which breaks in two places, leaving a free drop which falls out, Fig. 4(c).

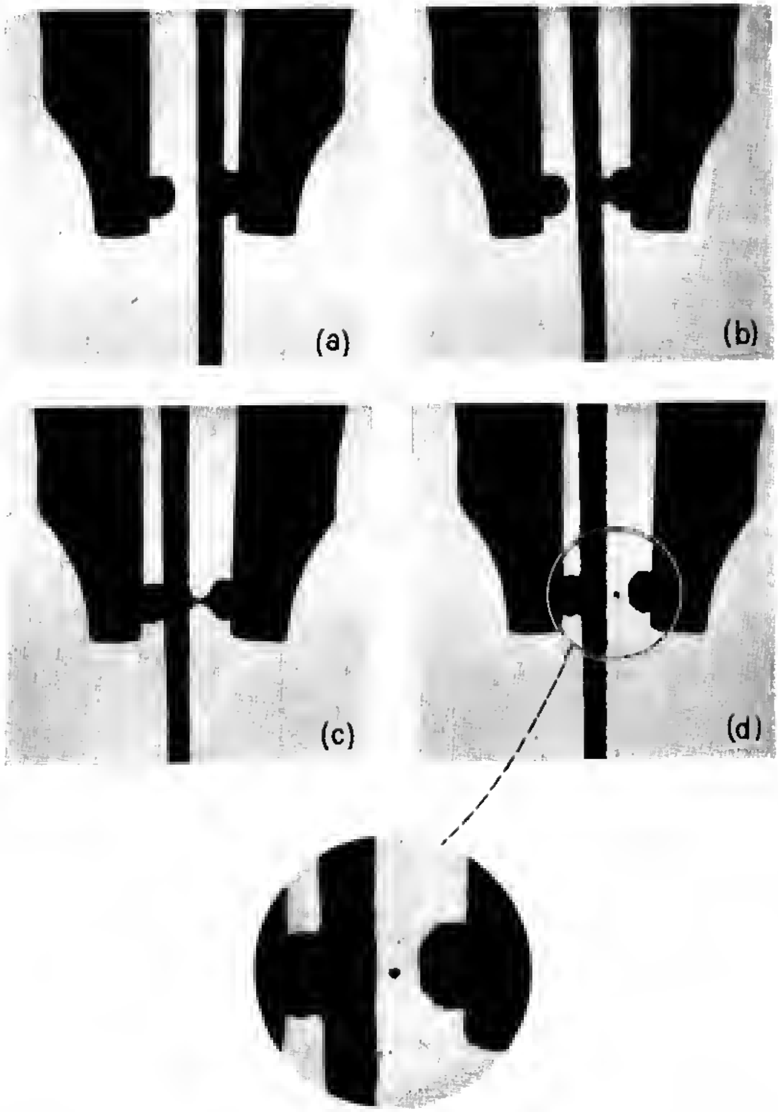

Fig. 4 — Dynamics of mercury contact. (a) Armature against contact on right. Note spherical shape of mercury on left contact. (b) Armature moves to left, drawing out mercury bridge. (c) Armature further to left; bridge about to break. (d) Armature reaches contact on left. Mercury bridge has broken in two places, leaving a tiny ball which later drops away.

When the ball falls out as the result of an operation, the loss of mercury results in a small, temporary constriction of the fillets in the grooves near the contact that was just opened. That is, the curvature of the surfaces of these fillets becomes more negative. As shown by equation (1), this produces a local decrease in liquid pressure. Mercury therefore flows up the armature from the reservoir to restore the normal static balance between surface tension and negative head. This is the fundamental behavior of an ordinary wick. The ball drops into the reservoir unless it happens to hit the armature on the way down. Thus, for repeated operations, there is a continuous circulation of mercury.

As indicated in Fig. 3, the fixed contact is a ball, with a flat surface where contact is made to the armature. In Fig. 4(c), taken directly after the breaking of the mercury bridge, the mercury remaining at the fixed contact on the right has been thrown back on the contact by surface tension forces, laying bare the flat surface. After several flow oscillations that are not shown, it comes to rest with the spherical contour shown by the contact at the left in Fig. 4(a). That is, being disconnected from the reservoir and having a limited wet surface to spread over, it assumes a positive head corresponding to a positive spherical radius about equal to that of the contact. This provides a mercury "cushion" in the form of a segment of a sphere, to which contact is made when the relay operates.

ADJUSTMENT OF SENSITIVITY

For various combinations of MMF's (magnetomotive forces) in the two magnets, various corresponding pairs of sensitivity values exist for operation in the two directions. A theoretical analysis of this relationship is given in the attached appendix. The adjustment of magnet strengths to obtain a specified pair of sensitivity values is made on the completed relay, using two electromagnets placed outside the can opposite the relay magnets. An automatic circuit is provided for this purpose that makes a complete adjustment in about 15 seconds, the time being dependent upon the precision required and the uniformity of the product being adjusted. The procedure used and the basis for it are discussed in the Appendix.

All of the adjustments used are of the type for which the armature moves all the way from one contact to the other when an operate current is applied. This represents the condition for the minimum differential ampere turns obtainable between the two operate values because it makes use of armature momentum.

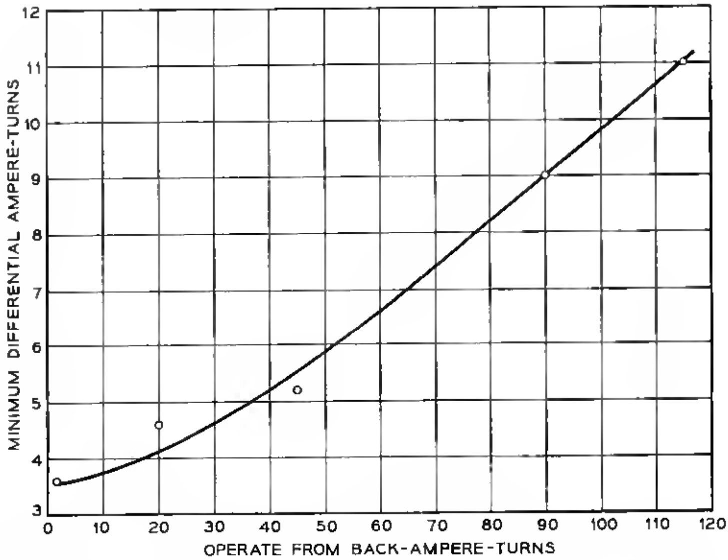

Fig. 5 — Minimum differential ampere turns as function of magnetic bias.

BIAS ADJUSTMENTS

As bias adjustments are made magnetically, rather than with the spring used in some polar designs, the armature flux tends to approach the same value at tbe operating points as it has in a balanced adjustment witb the same differential ampere turn value. Such difference as does enter witb increase of bias is due to differences in armature flux distribution between MMF introduced by tbe coil and that introduced by tbe magnets.

Tbe effect of bias is illustrated in Fig. 5, which shows the minimum differential ampere turn value obtainable in a relay as a function of the higber operate value. Tbe minimum differential value of 3.6 NI with a balanced adjustment is about tbe same as is obtainable with other polar relay designs. For operate values of about 100 ampere turns a "release to operate ratio" of about 90 per cent is obtained.

Larger differential ampere turn values, both with and without bias, are of course possible. The amount of bias obtainable in combination with larger differentials is somewhat reduced because of the greater magnet strengtb required.

EFFECT OF MAGNETIC SOAK ON SENSITIVITY

The effect of "soak" on sensitivity is illustrated in Fig. 6. It shows the change which takes place when the ampere turns to operate are

measured after applying a given ampere turn soak in each of two polarities.

SPEED OF OPERATION

Fig. 7 shows typical operate times of the relay for one balanced adjustment and one biased adjustment. The ordinates correspond to time to effect closure at the opposite contact after input is applied to the coil. The abscissae are shown both in terms of power in the full relay winding and the corresponding number of ampere turns. Two circuit conditions are indicated, one in which the voltage was applied directly to the full winding and the other in which the voltage was applied through a resistance equal to the coil resistance.

The winding used in this case is one which is specially designed for speed rather than sensitivity, being shorter in length, with the working gap near the middle. Its time constant (inductance-resistance ratio) is about 0.0006 second.

Fig. 8 shows "release" time measurements, where the relay, with various biased adjustments, was operated by opening the circuit. The curve is shown plotted against the "operate" setting of the relay. In this form it is relatively independent of the differential ampere turn adjustment.

The time required to open the contact from which the armature moves is typically about 0.0002 second longer than the closure time, as the

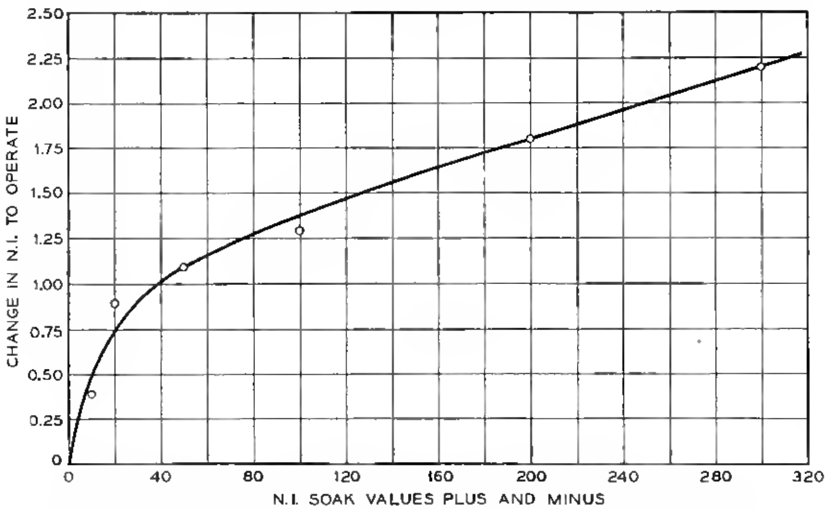

Fig. 6 — Change in NI. To operate versus plus and minus NI soak.

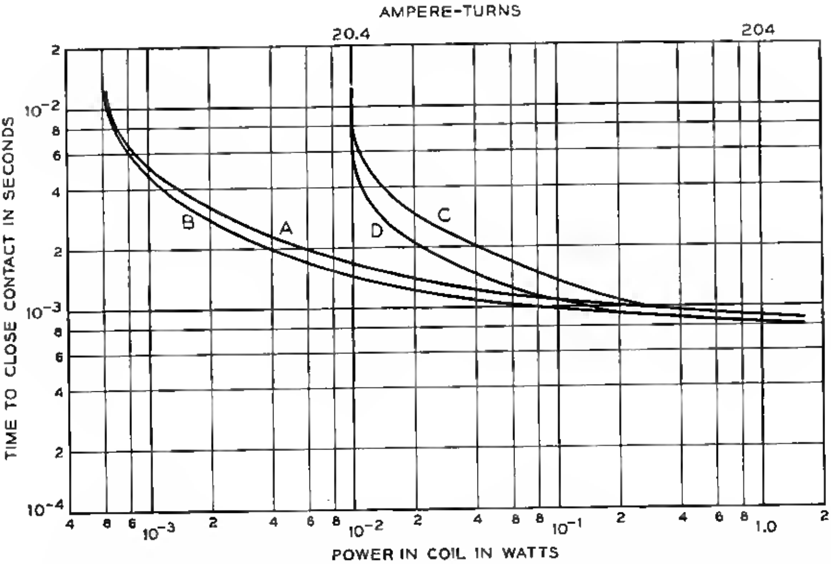

Fig. 7 — Time to close opposite contact after voltage is applied to coil. (A) ±5 NI adjustment, voltage directly on coil. (B) Same as (A), except with resistance equal to coil in series. (C) Operate +20.4 NI, release +9.9 NI voltage directly on coil. (D) Same as (C), except with resistance equal to coil in series.

mercury bridge does not ordinarily break until after contact is made on the opposite side.

The natural frequency of the free armature, wet with mercury, is about 220 cps. The relays have been used at frequencies up to about 350 cps where the drive conditions were individually selected with respect to the phase of impact transients. Fairly well controlled operation without such selection can be obtained up to about 100 cps.

CONTACTS

The relay has been designed with telephone, rather than power applications in mind. The contacts are smaller than those in the previous neutral design, and this appears to be associated with less capability for closure of very high current circuits. The capacity required across the contact to prevent noticeable arcing appears to be about the same as that required in the earlier type:

$$C = \frac{I^2}{10} \text{ microfarads,}$$

but in most cases, larger values than this will be needed to hold peak

voltages to safe values. A small resistance in series with the condenser to limit the closure current is usually necessary. A considerable amount of very satisfactory experience bas been had witb inductive loads of 0.5 ampere at 50 volts, with 0.5 mf in series with 10 ohms across the contacts.

The contact elosure shows no chatter for time intervals of 0.1 microsecond or more.

LIFE

Tests of relays with protected contacts indicate that the only change is a sensitivity ehange due to wear. Under conditions producing fairly high velocity of contact impact this change is of the order of 5 ampere turns increase in differential ampere turns for a billion operations, the change being roughly proportional to the logarithm of the number of operations.

HORIZONTAL TYPE RELAY

Most of the apparatus in the telephone plant is mounted on vertical panels. The substantially vertical mounting requirement for tbe relay shown in Fig. 1 tends therefore to be uneconomical from the space standpoint. Fig. 9 shows a modification of the glass enclosed switch which avoids this limitation by being designed to operate witb its axis horizontal.

The switch modification consists in adding to the switch a special

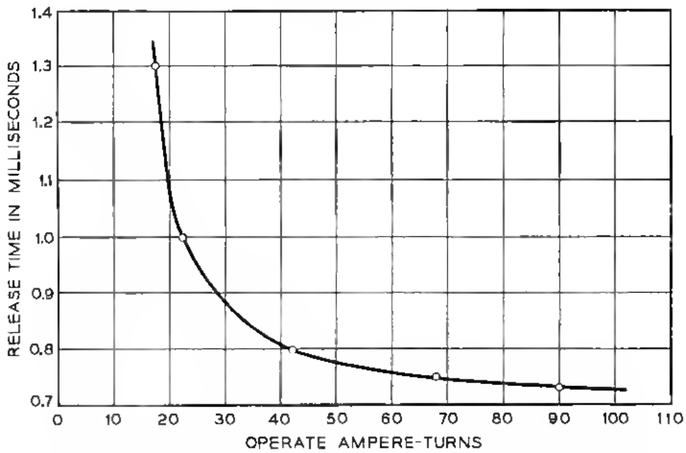

Fig. 8 — Release time versus operate ampere turn adjustment.

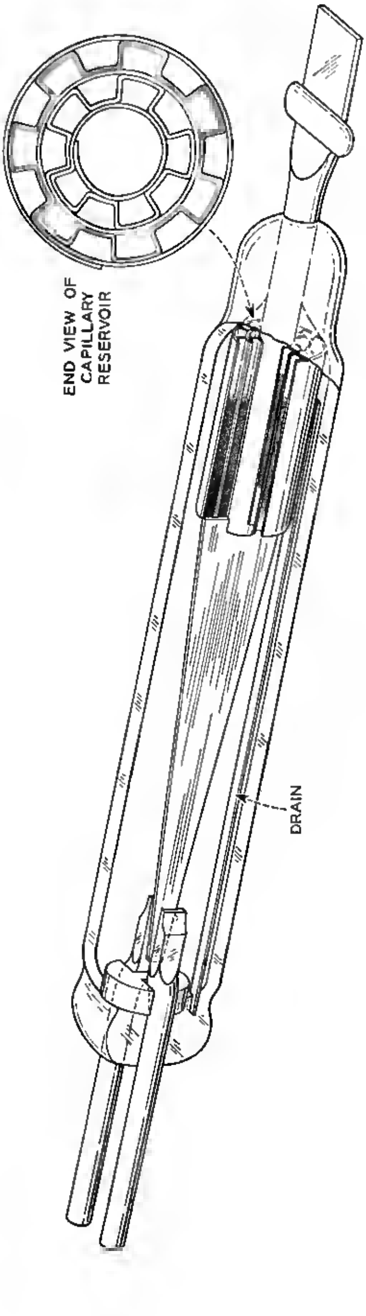

Fig. 9 — Horizontal switch.

capillary reservoir which establishes a negative head in the mercury equal to that obtained by the height of the contacts above the mercury reservoir in the switch shown in Fig. 2. To provide for the return of free mercury to the reservoir, a wet strip of metal is placed along the glass wall underneath the contacts.

The capillary reservoir is essentially a bundle of tubes with walls wet by the mercury. The amount of mercury in the switch is such that the tubes are about half full. The mercury menisci in these tubes are tangent to the walls and therefore have a spherical surface with a radius equal to that of the tubes. The proper tube radius ($R_1 = R_2 = 0.033$ cm) for

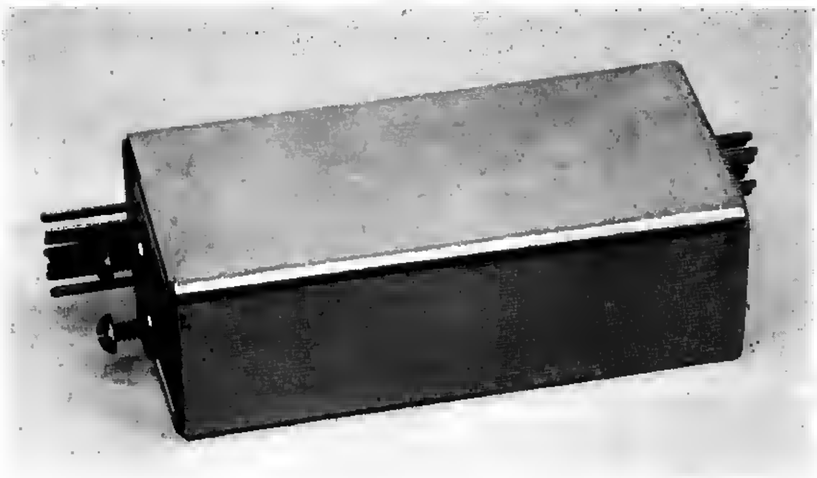

Fig. 10 — Horizontal relay.

the desired negative head ($h = 2.07$ cm) is obtained from equation (3). As the tubes have a uniform bore, the negative head which they establish is not critically dependent on the amount of mercury in them.

The capillary reservoir is made from thin strip, formed and then rolled into a cylinder. It surrounds the metal tube and is welded to the base of the armature. The drain element is sealed into the glass at one end, and, at the other end, is held in contact with the capillary element by the surface tension and negative head of the mercury.

The horizontal switch is an experimental design and has not been put into production. It can be assembled in the housing shown in Fig. 1 for plug connection to a vertical panel. Fig. 10 shows a preliminary model with the new type terminals for wrapped connections.[2] It is adapted for

[2] Solderless Wrapped Connections, B.S.T.J., May, 1953.

mounting on a vertical panel interchangeably with existing polar types. The terminals, which may be up to eight in number, are also brought out at the rear for test purposes.

HIGH-FREQUENCY SWITCHING

The small size, symmetry, and simplicity of the vertical switch structure has been found to be particularly well adapted for incorporation into coaxial structures for high-frequency switching and it is being used for a variety of applications of this kind.

USES

Small scale production of the relays has been started for a few special uses. Designs for larger scale uses are still in a preliminary stage. In general, it is expected that the relay will be well adapted for applications where a transfer contact in combination with low inductance, high speed, high sensitivity, low contact resistance, freedom from chatter, good high frequency switching characteristics, stability, long life, or any combination of these, is required.

APPENDIX

MAGNET STRENGTH VERSUS SENSITIVITY

A simplified representation of the magnetic system of a relay of this general type is shown in Fig. 11. Here the armature is shown working between two magnetic poles N and S, each of which has an area A. The armature position is indicated as a deviation ℓ toward N from the mid position, and is limited in its motion by stops at $\ell = \pm\ell_1$ from moving through the full magnetic gap range, defined by the positions $\ell = \pm\ell_2$.

M_s and M_n are MMF's in ampere turns, introduced by the magnets on either side, with positive values as indicated by the arrows. Similarly, M_c represents the MMF introduced by the operating coil. These values are not those of the magnets and coil in the actual relay. Instead they are assumed to be "Thevenin" equivalent open circuit values of MMF looking away from the working gaps on either side. The gaps are assumed to have the simple geometric dimensions of length $\ell_2 - \ell$ and $\ell_2 + \ell$, and area A. The reluctances looking away from the working gaps are assumed to be represented by the fixed gaps of area A and length $\ell_2 - \ell_1$ on either side.

The magnetic pull on the armature in a gap of this kind is

$$f = \frac{2\pi}{980} (0.1M)^2 \frac{A}{g^2} = \frac{(M)^2}{(124.9)} \frac{A}{g^2} \tag{1}$$

where f is the force in grams g is the gap length and M is the MMF in practical ampere turns across the gap.

In the structure shown, therefore, the net force on the armature from the gaps on both sides is

$$f_m = \frac{A}{(124.9)^2} \left[\frac{(M_n + M_c)^2}{(\ell_2 - \ell)^2} - \frac{(M_s - M_c)^2}{(\ell_2 + \ell)^2} \right], \tag{2}$$

where the values of M are expressed in ampere turns.

If $M_n = M_s$ this can be converted to

$$\frac{f_m}{f_{ml}} = \left[\frac{\left(1 + \frac{M_c}{M_n}\right)^2}{\left(1 - \frac{\ell}{\ell^2}\right)^2} - \frac{\left(1 - \frac{M_c}{M_n}\right)^2}{\left(1 + \frac{\ell}{\ell_2}\right)^2} \right], \tag{3}$$

where $f_{ml} = \left(\frac{M_n}{124.9}\right)^2 \frac{A}{\ell_2^2}$.

Fig. 12 shows curves of $\frac{f_m}{f_{ml}}$ versus $\frac{\ell}{\ell_2}$ for various values of $\frac{M_c}{M_n}$. Only one quadrant is shown as the system is symmetrical. It provides a convenient means for analysis of this type of relay.

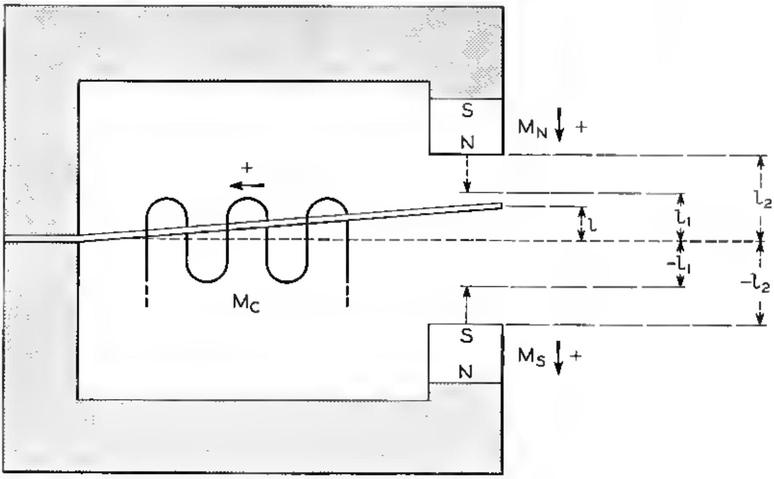

Fig. 11 — Simplified representation of relay.

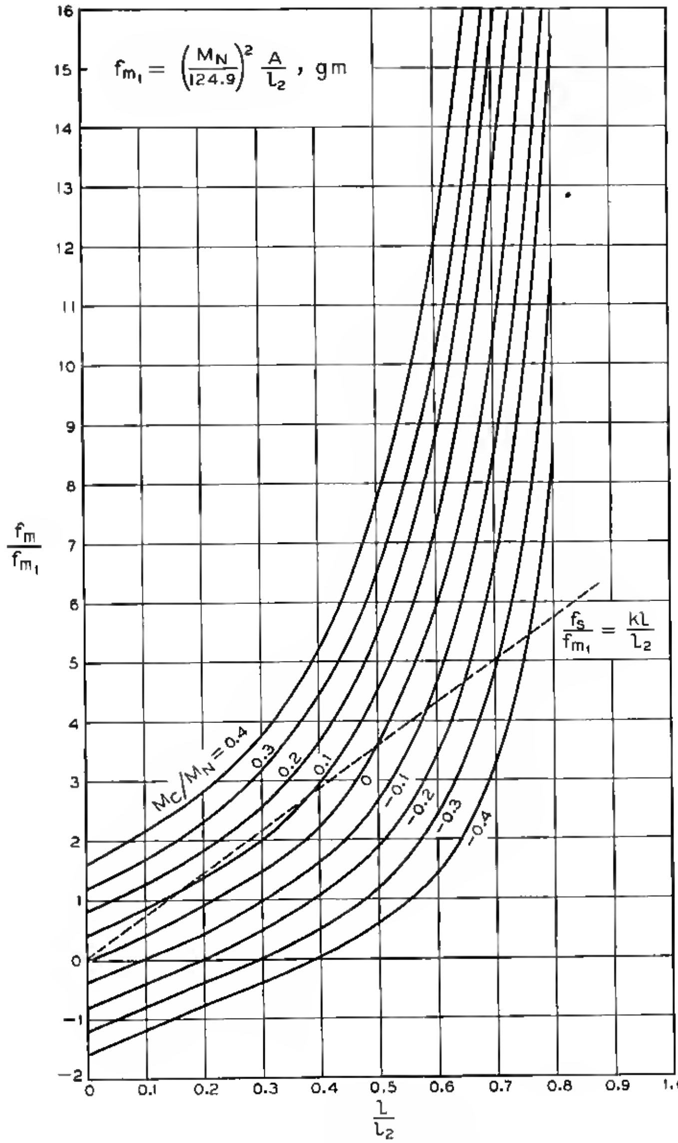

Fig. 12 — Balanced gap relay chart.

Also shown on the figure is a typical spring characteristic

$$\frac{f_s}{f_{ml}} = \frac{K\ell}{\ell_2}. \tag{4}$$

If the stops ℓ_1 and ℓ_2 are placed at points of intersection of the spring characteristic with the magnetic characteristic for $M = 0$, (in this case at $\ell_s/\ell_2 = 0.48$), we have a condition that corresponds to a hypothetical relay of infinite sensitivity. That is, the armature can be released from contact with either side with an infinitesmal coil input, and, if there are no magnetic or mechanical losses in its travel, it will just swing to the opposite side without any change in the total energy of the system. Let us define the magnet strength for this condition as M_0 and let us assume that $M_c = 0$ for operation in either direction with this magnet strength.

Assume now that the magnet strengths on each side are increased equally to the values

$$M_{n1} = M_{s1} = M_0 + \Delta. \tag{5}$$

For values of ℓ_1/ℓ_2 near 1 this change can be balanced out by a coil input of about the same amount, as practically all of the pull on the armature would be from the nearer pole. For values of ℓ_1/ℓ_2 near 0 the effect of a coil input will be equal and aiding in both gaps. The coil inputs required to just operate from the N and S poles, defined as M_{cn1} and M_{cs1}, respectively for this particular case, will be

$$M_{cs1} = -M_{cn1} = p\Delta = p(M_{n1} - M_0) = p(M_{s1} - M_0), \tag{6}$$

where p is a value between 1 and 0.5. Values for individual cases can be worked out with reference to the curves for various values of M_c/M_n in Fig. 12. For the case shown, where $\ell_1/\ell_2 = 0.48$, p is about 0.8.

An adjustment in accordance with (6) is thus a balanced one with a spread of $2p\Delta$ between the two sensitivity values, the amount of spread increasing with increase in the strength of the two equal magnets M_{n1} and M_{s1} above the value M_0.

A general type of adjustment, including all possible combinations of the two sensitivity values, can be obtained by adding a suitable value B to a balanced pair of sensitivity values in accordance with equation (6). These general sensitivity values would then be

$$\begin{aligned} M_{cs} &= M_{cs1} + B, \\ M_{cn} &= M_{cn1} + \mathrm{B}. \end{aligned} \tag{7}$$

This is the type of change that would be produced by a bias of $-B$

ampere turns in an auxiliary coil. The equivalent of such a bias would be obtained by decreasing the strength of the N magnet and increasing the strength of the S magnet, each by the value B. The general magnet strength values would then be

$$\begin{aligned} M_n &= M_{n1} - B, \\ M_s &= M_{s1} + B. \end{aligned} \tag{8}$$

Combining equations (5), (6), (7) and (8) to eliminate M_{cs1}, M_{cn1}, M_{n1}, M_{s1} and B, we obtain the general relations between sensitivity and magnet strength as

$$M_{cs} = \quad p\left(\frac{M_n + M_s}{2} - M_0\right) + \frac{M_s - M_n}{2}, \tag{9}$$

$$M_{cn} = -p\left(\frac{M_n + M_s}{2} - M_0\right) + \frac{M_s - M_n}{2}. \tag{10}$$

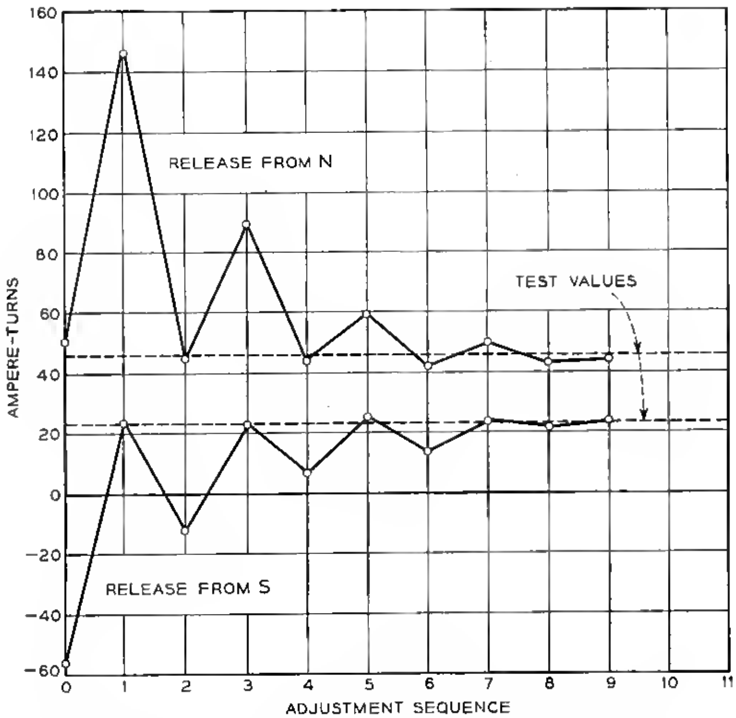

Fig.13 — Sequence of sensitivity values obtained in adjustment.

ADJUSTMENT OF SENSITIVITY

The procedure used to adjust the relay to any desired pair of sensitivity values is as follows:

1. Magnetize the two magnets fully by a flux directly across them.
2. With the armature starting from one side, progressively decrease the magnetization on that side in small steps until the armature just operates to the other side on the final current value desired for this direction of operation.
3. With the armature starting on the other side, progressively decrease the magnetization on that side in small steps until the armature just operates from that side on the final current value desired for this second direction of operation.
4. Repeat 2 and 3 alternately until the relay just operates in both directions on the two current values desired.

Within limitations such as the size of demagnetizing increments used per step, this procedure results in an adjustment to the two test values used. Let us consider why this result is obtained.

If we should substitute $p = 1$ in equations 9 and 10 we would obtain

$$M_{cs} = M_s - M_0 ,$$
$$M_{cn} = M_1 - M_n .$$

That is, in such a case, the two adjustments would be independent of each other and the above process would require only one adjustment of each magnet. In the more general case, where the force on the armature is affected by both poles, each adjustment on one side results in a greater magnet strength at the pole being adjusted than is required for the final adjustment, because of the pull from the opposite pole, the amount of which is greater than normal because that pole has not been reduced to its final magnet strength. Thus the final adjustment is normally reached through a number of alternations between the two sides, which progressively approach the final pair of sensitivity values.

The sequence of sensitivity values obtained in a typical adjustment of this kind is shown in Fig. 13.